FTD-HT-23-1089-68

FOREIGN TECHNOLOGY DIVISION

DEEP DRAWING OF MOLYBDENUM AND ITS ALLOYS

by

V. N. Korolev and L. A. Shofman

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FTD-HT-23-1089-68

EDITED TRANSLATION

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English pages: 19

Source: Kuznechno-Shtampovochnoye Proizvodstvo (Forging and Stamping), No. 10, 1967, pp. 17-23.

Translated by: D. Koolbeck/TDBRO-2

PREPARED BY:

TRANSLATION DIVISION
FOREIGN TECHNOLOGY DIVISION
WP-AFB, OHIO.

DATA HANDLING PAGE				
01-ACCESSION NO. TP9000052	98-DOCUMENT LOC	39-TOPIC TAGS metal drawing, molybdenum alloy, molybdenum property		
09-TITLE DEEP DRAWING OF MOLYBDENUM AND ITS ALLOYS				
47-SUBJECT AREA 13				
42-AUTHOR/CO-AUTHORS KOROLEV, V. N.; 16-SHOFMAN, L. A.				10-DATE OF INFO --OCT67
43-SOURCE KUZNECHNO-SHTAMPOVOCHNOYE PROIZVODSTVO (RUSSIAN)				68-DOCUMENT NO. FTD-HT-23-1089-68
				69-PROJECT NO. 72301-78
63-SECURITY AND DOWNGRADING INFORMATION UNCL, 0			64-CONTROL MARKINGS NONE	97-HEADER CLASN UNCL
76-REEL/FRAME NO. 1887 1894	77-SUPERSEDES	78-CHANGES	40-GEOGRAPHICAL AREA UR	NO OF PAGES 19
CONTRACT NO.	X REF ACC. NO. 65-AP7032045	PUBLISHING DATE 94-00	TYPE PRODUCT TRANSLATION	REVISION FREQ NONE
STEP NO. 02-UR/0182/67/000/010/0017/0023			ACCESSION NO.	

ABSTRACT

The effect of various technological factors on the capacity for deep drawing of commercial-grade sintered molybdenum and TaM-2 and Vm-1 molybdenum alloys has been investigated on flat specimens, 6mm wide and 0.5 and 0.8mm thick, cut from rolled sheets in the direction alone, and/or transverse, or at a 45 deg. angle to the direction of rolling. Test specimens in the annealed or strain-hardened condition were tested for mechanical properties under conditions of uniaxial and biaxial tension at temperatures of up to 500°C. Except for recrystallized sheet, the NDT temperature of all the investigated material was below room temperature. This showed that satisfactory parts can be produced from them by drawing at room temperature. The capacity for deep drawing depended mainly on the content of impurities, the microstructure and the deformation rate. Heating to 100-120°C significantly decreased the susceptibility to exfoliation and cracking and appreciably extended the technological use of the investigated metals. Static uniaxial tension tests did not adequately reveal the capacity of molybdenum sheet for deep drawing because of the anisotropy of mechanical properties in the sheet plane, and because of different behavior of molybdenum at linear and plane modes of the stressed state. The capacity for deep drawing was satisfactorily characterized by biaxial static tension tests with a fluid (in burst tests) or a rigid punch. This can be explained by the higher susceptibility of molybdenum to tensile tangential stresses at room temperature. The capacity

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of sheet molybdenum for deep drawing increased with increasing (to 70--90%) prestraining at cold or warm rolling. The experimental results showed also the feasibility of progressive multioperation deep drawing of thin wall parts from molybdenum and molybdenum-alloy sheets, with or without intermediate stress relieving. Depending on the sheet thickness, the direction of rolling and the heat treatment prior to drawing, the optimum temperature of drawing was within 220 to 350°C. Orig. art. has 8 figures and 2 tables.

DEEP DRAWING OF MOLYBDENUM AND ITS ALLOYS

V. N. Korolev and L. A. Shofman [Deceased]

One feature of the development of modern technology is the increase in the requirements for service properties of materials used in the manufacture of machines, devices, and instruments.

Sintered molybdenum and refractory alloys based on Mo represent promising materials for many branches of industry, thanks to their excellent high-temperature strength, good thermal and electrical conductivity, significant resistance to corrosion, and other important properties.

Difficulties are encountered during deep drawing of parts from sintered sheet Mo of type MCh (TsMTU/IMET No. 23-65) and from the alloys TsM-2A (ChMTU/TsNIIChM 1313-65) and VM-1 of technical grade at room temperature, owing to properties which are unsuitable for plastic deformation (large $\frac{\sigma_{0.2}}{\sigma_b} \approx 0.9$, small δ).

The stampability of molybdenum (especially in terms of deep drawing capacity) is influenced basically by the following factors: chemical composition, structure, and mechanical properties, while the variables connected directly with the conditions of deformation include the form of the stress-deformed state and the rate and temperature of deformation.

The plasticity of molybdenum alloys, and especially the temperature of the transition from the plastic to the brittle state, depend on the contents of carbon, oxygen, nitrogen, and hydrogen. Since the content of impurities in molybdenum alloys depends on the conditions of smelting, their room temperature plasticity is determined to a significant degree by metallurgical factors.

The solubility of inclusion elements in molybdenum is not large, and therefore the influence of these admixtures on its plasticity is particularly great. The reduction of the contents of these admixtures is of essential importance in lowering the transition temperature of molybdenum. Carbon and oxygen have the greatest effect on the transition temperature; thus, an increase in the content of oxygen from 0.0001% to 0.002% changes the transition temperature from -196°C to +25°C [1]. The presence of the carbide Mo_2C along the grain boundaries also lowers the ductility of molybdenum at room temperature and increases the temperature of the transition from the plastic to the brittle state. Therefore, in order to ensure obtaining a cold-brittleness temperature no higher than room temperature, the residual content of carbon in deoxidized molybdenum should not exceed 0.005% [2].

The mechanical properties of molybdenum alloys are also effected by the composition and quantity of alloying elements. Alloying of molybdenum with zirconium, titanium, and other elements (with the exception of rhenium) even in small quantities (up to 1%) increases the tensile strength and yield, reduces plasticity, and increases the temperature of the transition from the plastic to the brittle state. As can be seen from Figs. 1 and 2, in comparison with the alloy TsM-2A the investigated alloy VM-1 has a much higher tensile strength and yield and a smaller relative elongation, since on the average it contains two times more titanium and zirconium and 3-4 times more carbon.

Molybdenum at room temperature can be plastic and can also be brittle, depending on chemical composition, microstructure, stress condition diagram, degree of preliminary deformation, and the rate of deforming. But despite the fact that Mo is a refractory metal, its mechanical properties are essentially changed with a comparatively small increase in temperature (Figs. 1 and 2).

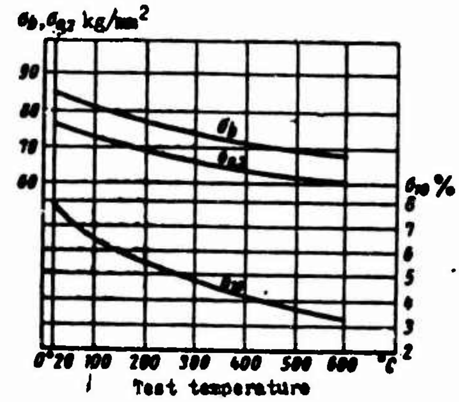

Fig. 1. Change in mechanical properties during testing on uniaxial tension of ten specimens 6 mm wide and 0.8 mm thick of the alloy VM-1 along the direction of rolling, depending on the temperature of deformation. The specimens were annealed in a vacuum of $1 \cdot 10^{-4}$ mm Hg at 1070°C with aging for 1.5 h.

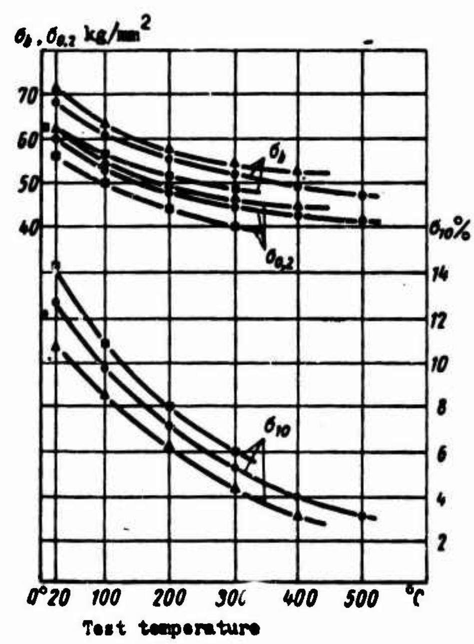

Fig. 2. Change in the mechanical properties during uniaxial testing of 0.76 mm thick specimens of cross-rolled alloy TsM-2A: ●—● direction of cold rolling; ▲—▲ across cold rolling; ■—■ at an angle of 45° to the direction of cold rolling.

The degree of preliminary deformation achieved during rolling has an essential effect on the mechanical properties of molybdenum alloy sheets. The plastic properties of molybdenum alloys depend on their structure, and during crystallization the lower-melting impurities are separated along the grain boundaries; this is one of the fundamental causes of low plasticity of sheet alloys. During deforming by rolling, brittle interlayers along the grain boundaries are destroyed and plasticity increases. The much higher plasticity of molybdenum with a thin-fiber structure resulting from a high degree of preliminary deformation (up to 70-90%) can be explained by destruction of the liquation net of impurities along the grain boundaries, the increase in the areas of grain surface, and the decrease in the concentration of nonmetallic inclusions per unit surface. With rolling in one direction, the structure of molybdenum alloys takes on a banded character and the anisotropy of the mechanical properties grows with an increase in the degree of deformation. Therefore, for deep drawing it is advisable to use sheets which have been rolled in two mutually perpendicular directions (cold rolling perpendicular to hot).

Experiments on deep drawing were conducted with blanks of molybdenum MCh and the alloys TsM-2A and VM-1. Specimens 6 mm wide and 0.5 and 0.8 mm thick were prepared from the same sheets as the disk blanks. The specimens were cut along, across, and at a 45° angle to the direction of rolling for uniaxial tension and specimens with dimensions of 90 × 90 mm were prepared for biaxial tension.

The microstructure of the alloy TsM-2A prepared by cross rolling along the surface of the sheet does not have a clearly expressed texture, and the mechanical properties of the metal are little distinguished in the two mutually perpendicular directions of rolling (Fig. 2).

As was shown by the tests under uniaxial and biaxial tension, the temperature of the transition from the plastic to the brittle state in molybdenum MCh and in the alloys TsM-2A and VM-1 is lower than room temperature (with the exception of a recrystallized sheet), and therefore parts with a good quality of drawing can be obtained at room temperature. However, it is a characteristic feature of molybdenum alloys that plasticity at room temperature varies strongly depending on the rate of deformation. The tendency to lamination and spalling during drawing of alloys TsM-2A and VM-1 from an initial thickness of 0.8 mm is strongly increased at a deformation rate v = 30-35 mm/s, other conditions being equal. At much higher temperatures the effect of deformation rate on the stampability of molybdenum is strongly decreased. For example, for the alloy TsM-2A at 100°C an increase in the speed of the punch at the beginning of the drawing process to 200 mm/s at k_1 = 0.58-0.60 leads to 20-25% spoilage, while at 250-300°C the capacity of molybdenum for drawing is virtually unchanged. Here heating increases the stampability of molybdenum in both the annealed and the delivered (peened) states. The influence of the deformation rate on the stampability of molybdenum at room temperature is explained by the fact that the temperature of the transition of MCh molybdenum of industrial grade and of the alloys TsM-2A and VM-1 is close to room temperature. In view of this, an insignificant displacement of the brittleness threshold with an increase in the deformation rate is accompanied by transition of the molybdenum from the plastic to the brittle state.

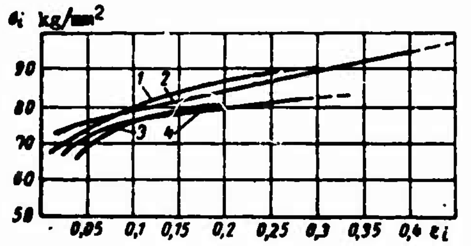

Fig. 3. Dependence $\sigma_i = f(\varepsilon_i)$, obtained by hydrostatic testing of molybdenum and its alloys annealed in a vacuum of $1 \cdot 10^{-4}$ mm Hg: 1) alloy VM-1 0.8 mm thick, annealed at 1070°C, 1.5 h; 2) sintered MCh molybdenum 0.82 mm thick, annealed at 90°C, 35 min; 3) alloy TsM-2A cross-rolled to a thickness of 0.49 mm, annealed at 1070°C, 1.5 h; 4) alloy TsM-2A cross-rolled to a thickness of 0.76 mm, annealed at 1070°C, 1.5 h.

Hydrostatic tests under biaxial tension showed that as a result of the greater stability in these conditions than was obtained during testing with uniaxial tension, molybdenum permits attaining greater evenness of plastic deformation. Figure 3 shows the relationship $\sigma_i = f(\varepsilon_i)$, constructed as a result of tests for molybdenum MCh and for the alloys TsM-2A and VM-1 [3]. From the results of these tests, it is possible to determine the magnitude of intensity of $(\sigma_i)_k$ and $(\varepsilon_i)_k$ at the moment of loss of stability:

$$(\sigma_i)_k = \frac{p_{max} R}{2t_k}; \quad (\varepsilon_i)_k = \ln \frac{t_k}{t_0},$$

where p_{max} is the maximum pressure of the fluid during the test;
t_k is the final thickness of the metal at the pole of the lune;
R is the radius of curvature of the surface of the lune at the pole at the moment of loss of stability (maximum pressure).

Since the biaxial hydrostatic tests were accompanied by significant noncoincidence of the mechanical properties (especially for the alloys TsM-2A and VM-1), Fig. 3 shows the average relationships $(\sigma_i)_k = \sigma_i = f(\varepsilon_i)$ [the broken line shows the dependence $(\sigma_i)_k = f(\varepsilon_i)_k$ which was observed in individual specimens].

As is evident from Fig. 3, the greatest deformation without destruction was obtained during drawing of molybdenum MCh. The greatest local deformation at the moment of destruction of the specimen during hydrostatic biaxial tension testing was less than that during uniaxial testing. Thus, for example, during biaxial tension the local relative reduction of thickness of the blank at the moment of rupture comprised 36% for MCh and 25% for TsM-2A, while at the same time under conditions of uniaxial tension the relative reduction of area of a transverse section of the specimen upon destruction achieved the following values: 54% for MCh and 32.5% for TsM-2A. Thus, with molybdenum under biaxial tension the uniform phase of deformation is increased at the expense of a corresponding reduction of local deformation, and the total deformation at destruction of the metal is reduced in comparison with that under conditions of uniaxial tension. In conditions of the plane stressed state (for example, reduction of an MCh sintered molybdenum tube at room temperature in a radius and conical die without exit into the cylindrical part of the die, i.e., with compressive meridional and tangential stresses), reduction is possible with coefficients which are equal to or less than the reduction factors for low-carbon steel [4]. During reduction [5] molybdenum can be subjected to significant deformation without special supplementary heating or intermediate annealing (since the die consists of spheres there is a resultant reduction of contact with the blank at the side of deformation, a reduced coefficient of friction, and an absence of components due to the action of friction forces on the cylindrical shoulder of the dye in comparison with the case of drawing with thinning; therefore, molybdenum undergoes reduced axial tensile stresses as compared with the case of a one-piece die).

In view of the fact that specifications permit an oscillation in the content of impurities in the chemical composition of molybdenum, and also because of the high sensitivity at room temperature of molybdenum to tensile tangential stresses and to an increase in the rate of deformation, to reduce spalling and lamination it is advisable to apply preheating in industrial conditions. Preheating of molybdenum significantly improves its stampability and expands the range of its technological capabilities. Thus, for example, during press working of thin-walled parts from MCh molybdenum the friction of the bronze hard wedge around the molybdenum blank causes an increase in the temperature of the blank up to 100-120°C, and in one elementary operation of the wedge parts are prepared with the ratio $\frac{h}{d}$ = 2 and higher [6] (where h is the height of the part and d is the diameter of the part).

Lamination is a form of brittle destruction, in which the cracks are directed parallel to the surface (in the plane of the sheet) and separate the sheet into several layers. Experience has shown that lamination usually occurs in strongly cold-worked sheets. During drawing, even preheated high-quality blanks undergo spalling and lamination. One of the main causes of spalling and lamination is nonuniformity of the structure and properties from one sheet to another and even within a single sheet of contemporary industrial rolling production. The brittleness of molybdenum is connected with dislocation phenomena, that is, with interaction of dislocations and grain boundaries [7]. Lamination of molybdenum depends on the content of oxygen and nitrogen. The more oxygen and nitrogen the molybdenum contains, the greater is the tendency to lamination. In highly refined molybdenum no lamination was observed either during testing or during drawing. To reduce the tendency to spalling and lamination polygonization should not be permitted to go to completion along the grain boundaries in molybdenum.

In connection with the fact that molybdenum possesses high thermal conductivity and low heat capacity and, therefore, is heated and cooled more quickly than steel, during sheet stamping with preheating it is necessary to heat the equipment.

Basically, experiments on the first and subsequent operations of drawing molybdenum and its alloys were conducted on a stamp — an instrument with hydraulic springs and with built-in electric heaters. The experiments were conducted with change of the rate of deformation within the limits of 3-50 mm/s. Experiments were also conducted with a change in the speed of the tool within a range of 85-250 mm/s at the beginning of drawing on a crank press with various temperatures of deformation*.

In production conditions parts are stamped on a TG-60 single-action press on a specially constructed stand (Fig. 4) with guide columns cooled by running water and with changeable die and punch. This ensures good coaxiality of the punch and die and its rapid readjustment. The press force is created directly by springs which are placed outside the zone of heating. The pressing flange and the punch are heated by transfer of heat from the die.

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*A. I. Galakhov took part in the work.

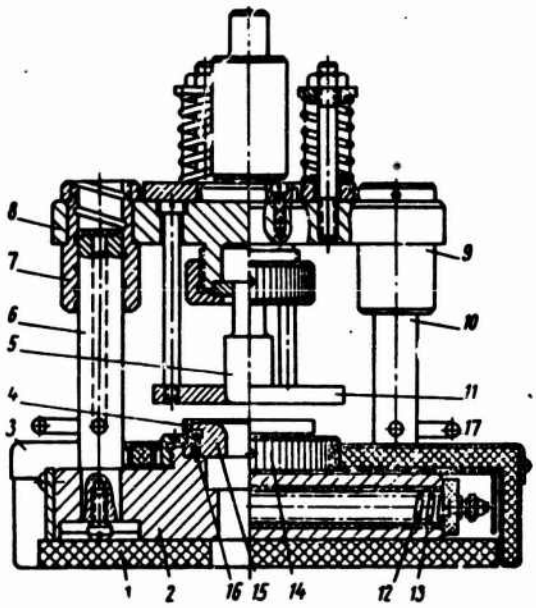

Fig. 4. Press for drawing parts with preheating: 1) asbestos cement packing; 2) lower plate; 3) shell; 4) locator; 5) punch; 6 and 10) columns; 7 and 9) guide bushings; 8) upper plate; 11) pressing device; 12) coil; 13) insulator; 14) nut; 15) die; 16) screw for attaching thermocouples; 17) pipeline.

During deep drawing of parts from molybdenum there is some hardening. Reduced hardenability is characteristic of cold rolled sheets. Thus, after three operations with a blank of alloy TsM-2A without intermediate annealing the total degree of deformation comprised 65%, while the hardness had increased from a value for the blank of HV 235-240 up to HV 255-261 kg/mm^2 (with a load p = 30 kg).

As can be seen from Fig. 3, the intensity of hardening of TsM-2A is less than that in VM-1 or in MCh; this may be explained by the greater degree of preliminary deformation in TsM-2A and the smaller percentage content of alloying elements in it as compared with alloy VM-1. After a significant degree of deformation during deep drawing without intermediate annealing, hardening and the appearance of large residual stresses result in the manifestation of cracks; therefore, it is necessary to carry out intermediate annealing before subsequent operations of drawing once a total degree of deformation ε = 55-65% has been achieved. During subsequent drawings which exceed this deformation spalling will occur along the ears, i.e., at an angle of 45° to the direction of rolling.

With an optimal temperature of annealing, a fine fiber deformation structure is secured after the removal of residual stresses; this imparts to the molybdenum high plasticity.

To clarify the influence of the state of the molybdenum on its stampability, the first drawing was conducted using sheets of MCh molybdenum 0.82 mm in thickness both in the delivered state (peened) and after annealing in a vacuum of $1 \cdot 10^{-4}$ mm Hg at 890°C with holding for 35 min and at 1070°C with holding for 1.5 h. Figure 5 shows the change in mechanical properties of MCh molybdenum under under uniaxial tension, depending on the temperature of deformation. Molybdenum in the delivered state has an increased tendency to folding and lamination during drawing and upon heating at 220-260°C the working coefficient k_1 = 0.62-0.64. Molybdenum which has been annealed in vacuum at 1070°C with holding for 1.5 h develops brittle cracking at the beginning of deformation during tests under biaxial tension imparted by a fluid and a rigid punch (punching out lunes). During uniaxial tension testing molybdenum annealed at this regime (speed of motion of the clamps v = 1.2 mm/min at 20°C) has $\frac{\sigma_{0.2}}{\sigma_b}$ = 0.79 and δ_{10} = 2.0%. However, in drawing of sintered MCh molybdenum annealed in vacuum at 1070°C with holding for 1.5 h and with k_1 = 0.57-0.60, even with heating up to 350°C spoilage up to 80% was obtained (rate of deformation v = 3 mm/s). Sintered molybdenum annealed in a vacuum at 1070°C with holding for 1.5 h is recrystallized, and the transition temperature strongly depends on the degree of recrystallization and on the content of admixtures.

As was shown by experiments on deep drawing, the optimum regime for sintered MCh molybdenum should be considered to be annealing in vacuum at a temperature of 880-900°C with holding for 30-40 min. Molybdenum MCh annealed in this regime with k_1 = 0.6 yielded drawn parts of good quality at room temperature.

Consequently, the indices of plasticity under uniaxial tension do not characterize the capacity of molybdenum for deep drawing, owing to the various diagrams of the stress state and to the high rate of deformation during drawing.

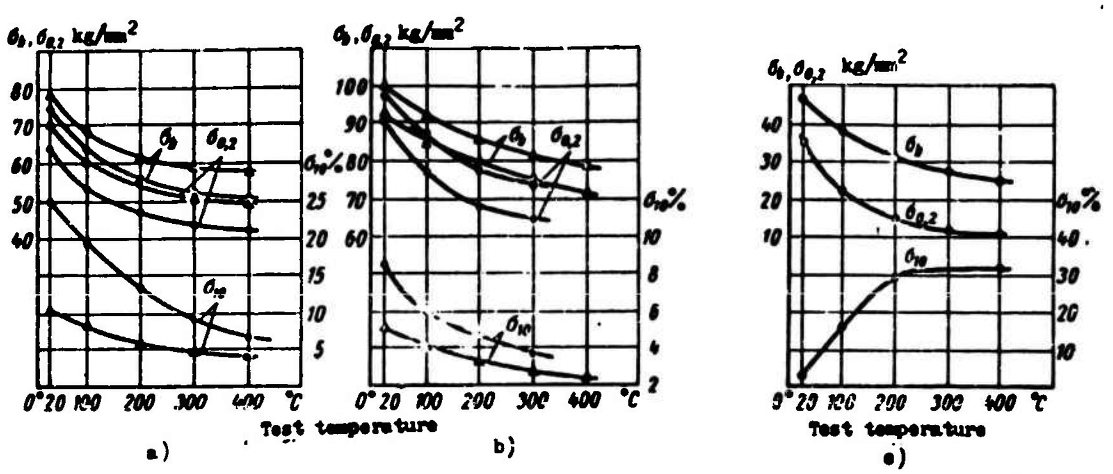

Fig. 5. Change in the mechanical properties of sintered MCh molybdenum 0.82 mm thick under uniaxial tension, depending on the temperature of deformation: a) annealed in a vacuum of $1 \cdot 10^{-4}$ mm Hg at 890°C, 35 min; b) in the delivered state; c) annealed in a vacuum of $1 \cdot 10^{-4}$ mm Hg at 1070°C, 1.5 h, thickness 0.81 mm; ●—● along the direction of rolling; ▲—▲ across the direction of rolling.

It follows that the optimum annealing for the alloys TsM-2A and VM-1 is annealing in a medium of hydrogen or in a vacuum furnace at 1060-1080°C and at a residual pressure of no less than $1 \cdot 10^{-4}$ mm Hg with holding for 1.5 h.

Investigation of the microstructure of stamped parts showed that there were no particular differences in the structure as compared with the structure of molybdenum in delivered condition.

The influence of anisotropy on the process of drawing sheet molybdenum is manifested in the appearance of ears on the flange or wall of the part. Ears in the molybdenum are formed at an angle of 45° to the direction of rolling, i.e., in the direction in which the smallest resistance to deformation and the largest δ are found.

Experience in the deep drawing of various forms of sheet blanks has shown that the stampability cannot be characterized by the results of tests on unaxial tension [8]. Therefore optimum (working) coefficients of elongation for drawing small cups have been determined for molybdenum and its alloys, depending upon the relative thickness

Table 1.

Type and state of molybdenum and its alloys	Initial thickness t_0 in mm	Uniaxial tension (direction of rolling) $\frac{\sigma_{0.2}}{\sigma_b}$	Uniaxial tension (direction of rolling) δ_{10} in % at 20°C	Biaxial tension, Hydrostatic $\left(\frac{\Delta t}{t_0}\right)_K$	Biaxial tension, Hydrostatic: Depth of the lune in mm	Lune depth per Erickson in mm (R = 10 mm without lubricant)	Relative thickness $\frac{t_0}{D}100$ in %	Working (optimum) coefficients, Without intermediate annealing: k_1	k_2	k_3	With intermediate annealing: k_4	k_5	k_6	Temperature of deformation in °C (die temperature)
MCh, annealed in vacuum of $1\cdot10^{-4}$ mm Hg, 890°C, 35 min	0.52	0.875	12	0.29	11.9	7.0	0.91	0.6-0.62	0.75-0.77				--	220-260
MCh, annealed in vacuum of $1\cdot10^{-4}$ mm Hg, 890°C, 35 min	0.82	0.87	25	0.36	14.1	8.0	1.36	0.57-0.59	0.73-0.75	0.80-0.82	0.84-0.86	0.86-0.88	0.88-0.90	220-260
TsM-2A, cross rolled, annealed in vacuum of $1\cdot10^{-4}$ mm Hg, 1070°C, 1.5 h	0.49	0.85	11	0.18	10.2	5.8	0.86	0.61-0.63	0.75-0.77					250-300
TsM-2A, cross rolled, annealed in vacuum of $1\cdot10^{-4}$ mm Hg, 1070°C, 1.5 h	0.75	0.88	12.6	0.25	12.5	7.4	1.26	0.58-0.60	0.73-0.75	0.80-0.82	0.84-0.86	0.86-0.88	0.88-0.90	250-300
TsM-2A, cross rolled, annealed in vacuum of $1\cdot10^{-4}$ mm Hg, 1070°C, 1.5 h	0.81	0.91	7	0.20	10.5	-	1.35	0.60-0.62	0.74-0.76	0.81-0.83	0.84-0.86	0.87-0.90	--	280-350
VM-1, annealed in vacuum of $1\cdot10^{-4}$ mm Hg, 1070°C, 1.5 h	0.8	0.905	8	0.22	11.2	6.2	1.34	0.60-0.62	0.74-0.76	0.81-0.83	0.84-0.86	0.88-0.90	0.90-0.92	280-350
MCh, annealed in vacuum of $1\cdot10^{-4}$ mm Hg, 1070°C, 1.5 h	0.81	0.79	2	Brittle spalling at beginning of extrusion			1.35	Spalling at 20°C and large percentage of waste due to spalling during drawing k_1 = 0.57-0.60 with heating to 350°C at low rates of deformation (up to 10 mm/s)						

Notes: 1. At deformation rates of 150-200 mm/s one should select a higher value of the working coefficients.

2. We took: $k_p = (1.05\text{-}1.03)k_{np}$, (where k_{np} is the limit drawing rate, $k_{np} = \frac{d}{D}$; d is the average diameter of the drawn cup; D is the diameter of the blank).

3. The lubricant was aqueous colloidal graphic preparations V-0 and V-1, GOST 5245-50.

4. Punch temperature was 100-140°C less than the temperature of heating of the die.

of the blanks, and with corrections for the temperature and deformation depending on the chemical composition, structure, mechanical properties, and rate of deformation. These optimal coefficients are given in Table 1.

The first drawing operation was conducted in a die with a diameter of 35 mm with a conical input flare during drawing without clamping and in a die with a radius edge during drawing with a clamp. A series of experiments were conducted with a different magnitude of the gap between the punch and the die. In certain experiments the blank clamping was accomplished by means of a motionless clamp plate, while in others clamping force was applied directly on the blank. The magnitude of the radius of chamfering of the working parts of the stamp, especially the working edges of the die, had a great influence on the drawing process. Small radii of chamfering of the working edges of the die, $r_m < 3\ t_0$, at $k_1 = 0.56$-0.60 lead to an increase in tensile stresses in the molybdenum, to thinning up to 25-30%, and to fractures.

During drawing with subsequent calibration it is possible to obtain tapered parts with radii which are equal to or less than the initial thickness of the blank. The optimum value of r_m depends mainly on the magnitude of the elongation factor. When selecting the elongation factor it is necessary to consider the magnitude of the permissible thinning of the walls of the stamped part.

In order to obtain high quality parts by drawing in the smallest possible number of operations, fulfilled with the greatest possible degree of deformation without intermediate annealing, and so that thinning of the walls in the critical sections will not exceed 12-14%, one should have small $r_{m1} \geq 5\ t_0$, and $r_{n1} > 4.5\ t_0$ (r_{n1} is the radius of the punch of the first operation; t_0 is the initial thickness of the blank).

For deep drawing of molybdenum and molybdenum alloys one can recommend in the first operation these values: $r_{m1} = (6$-$8)t_0$; $r_{n1} = (0.9$-$1)\ r_{m1}$, and as the positive gap in the first operation

S_1 = (1.10-1.15)t_0; for subsequent operation S = (1.05-1.10)S_1.

With the molybdenum alloys TsM-2A and VM-1 in conical and radius dies with blank holders the first drawing is carried out with the gap S_1 = (0.8-0.9)t_0 with the degree of deformation [9]

$$\varepsilon = 1 - \frac{dt_1}{Dt_0} = 1 - m_d m_t \approx 0{,}48,$$

where $m_{d1} = \frac{d}{D} = \frac{34.4}{55} = 0.6$ is the elongation factor along the change of diameters (without thinning); $m_{t1} = \frac{t_1}{t_0} = \frac{0.7}{0.81} = 0.864$ is the thinning factor; t_1 is the wall thickness after the first operation.

After drawing with a gap of (0.8-0.9)t_0 parts are obtained with a high accuracy in terms of diameter and with surfaces close to cylindrical.

In drawing molybdenum without clamping the first operation was conducted in conical dies with conicity of 15, 22, 30, and 35° with an additional phase diameter of the die cone D_1 = 0.9 D (D is the diameter of the blank). When the gap is equal to the initial thickness of the blank, elastic deformation of the part in the stamp leads to a certain increase in the gap and traces from straightening of folds are noted on the parts. In a die with a conicity of 30° and a gap of S_1 = (0.95-0.97)t_0 the limit elongation rate k_{np} = 0.7 for alloys TsM-2A and VM-1 while for MCh annealed in vacuum at 890°C and held for 30 min, k_{np} = 0.67 when $\frac{t_0}{D}100 \geq 1.55\%$.

The blank-clamping force Q which is necessary to prevent formation of folds during drawing is determined by the formula

$$Q = qF,$$

where q is the specific clamping force in kG/mm^2; F is the area under the clamp in mm^2.

The specific clamping force for molybdenum and its alloys is given in Table 2.

Table 2.

Molybdenum	State of the molybdenum	Deformation temperature, °C	q in kg/mm^2
MCh	Annealed in vacuum of $1 \cdot 10^{-4}$ mm Hg at 890°C, 35 min	220-260	0.45-0.60
TsM-2A	Annealed in vacuum of $1 \cdot 10^{-4}$ mm Hg at 1070°C, 1.5 h	250-300	0.40-0.60
VM-1	Annealed in vacuum of $1 \cdot 10^{-4}$ mm Hg at 1070°C, 1.5 h	280-350	0.5 -0.65

Notes: 1. Table 2 gives average experimental values of specific blank-clamping force during drawing with k_{pl}, shown in Table 1.

2. Larger values of q should be selected for thinner sheets of molybdenum.

Subsequent drawing operations were conducted without clamping both in radius dies and in conical dies with cone angle α = 10, 12, 14, 15, 17, 18, 20, 25, and 30°.

In the second drawing operation in a die with $r_m \geq 10\ t_0$ and $k_2 = 0.73$ fold formation occurs (with the passage of the upper edges of the part along the rounded part of the die) along the curves and projections (ears), i.e., along, across, and at a 45° angle to the direction of rolling. With the passage of the upper edge of the part through the cylindrical part of the die the folds are straightened, but the quality of the part is lessened.

For subsequent drawings we can recommend $r_m = (0.7\text{-}0.85)r_{m1}$, and $r_n = (0.7\text{-}0.9)r_m$; here in a radius die it is necessary that the condition $d_m + 2r_m \geq d_n$ be fulfilled (d_m is the internal diameter of the die; d_n is the external diameter of the part).

As the experiment showed, the optimum angle of conicity of the die for the second and subsequent drawing operations should be considered to be α = 14-17°. With a conicity greater than 18° the molybdenum does not fit to the conical surface of the die along the whole length, but strives to occupy a position close to the position with an optimal angle.

The second and subsequent drawing operations are carried out with a reactive strip with total neutralization of the effect of the bending moment which arises due to tensile tangential stresses.

Reverse drawing of molybdenum and its alloys can be conducted with the same working coefficient as ordinary (direct) drawing, i.e., k_2 = 0.73-0.75 and k_3 = 0.80-0.83; however, the application of clamping during the second operation is mandatory and the rate of deformation must be small. It is necessary that before subsequent operations (and especially before reverse drawing) the face of the part be trimmed to a smoothness of no less than ∇6.

Figure 6 shows the technological sequence of drawing a hemispherical cup from alloy TsM-2A with t_0 = 0.76 mm; here the third operation is reversed drawing with $k_3 = \frac{38.8}{48.5} = 0.80$.

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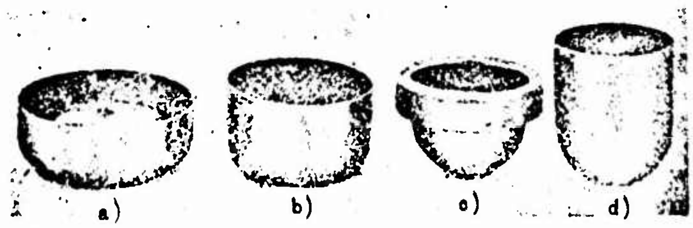

Fig. 6. Sequence of operations of drawing a hemispherical cup from alloy TsM-2A 0.76 mm thick from a blank with a diameter of 98 mm (ears cut off): a) first drawing; b) second drawing; c) reverse drawing, not to completion; d) part after reverse drawing.

Figure 7 shows square parts drawn from molybdenum and its alloys with t_0 = 0.8 mm. The parts are 33.4 × 33.4 mm in size. The two tall square parts were drawn with a working coefficient $k_k = \frac{r_u}{R_u} = \frac{5}{13} = 0.385$, with various disposition of the blank (calculated according to the method of V. P. Zvorono [10]) with respect to the die. Since molybdenum is an anisotropic metal, the positions of the blank in the corners relative to the direction of rolling have a very great significance (r_u is the angular radius of the die; R_u is the angular radius of the contour of the blank).

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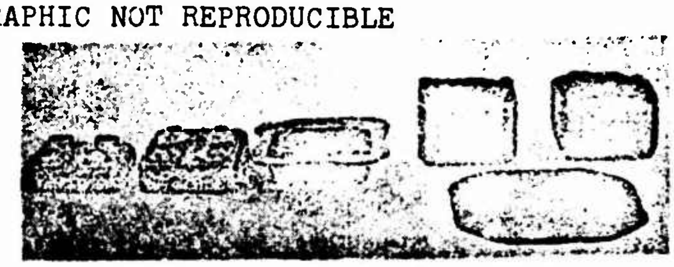

Fig. 7. Square parts 33.4 × 33.4 mm in size, obtained by drawing from molybdenum and its alloys; thickness 0.8 mm (the high square parts were drawn with a factor k_k = 0.385).

Figure 8 shows the technological sequence of seven operations of the drawing of MCh molybdenum with a total degree of deformation of 81%.

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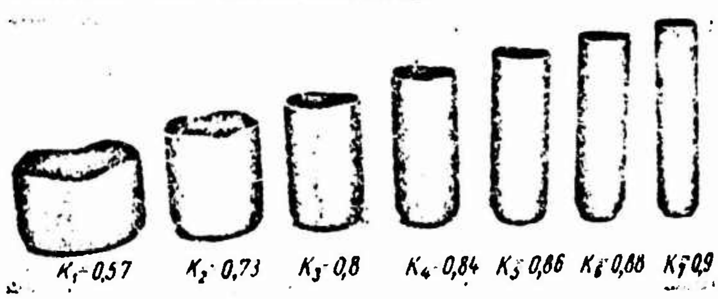

Fig. 8. Technological sequence of deep drawing of cups in seven operations from MCh molybdenum blanks 60 mm in diameter and 0.82 mm thick; total degree of deformation, 81%.

As is clear from Table 1, the degree of deformation with MCh molybdenum under biaxial hydrostatic tension is in satisfactory agreement with the degree of deformation achievable during drawing without heating and at low rates of deformation.

Conclusions. 1. The capacity for deep drawing at room temperature of sintered molybdenum and of alloys of molybdenum of industrial grade depends basically on the content of impurities, microstructure, and rate of deformation. Heating during deep drawing reduces the tendency of molybdenum to lamination and spalling, significantly improves its stampability, and expands its technological possibilities.

2. Static uniaxial tension does not characterize capacity of sheet molybdenum for deep drawing, due to the anisotropy of mechanical properties in the plane of the sheet, the different behavior of molybdenum in the case of linear and plane stressed state diagrams, and the high rate of deformation during drawing.

3. Biaxial static tests with liquid and rigid punch will satisfactorily characterize the suitability of molybdenum and its alloys for deep drawing. This is apparently explained by the high sensitivity of molybdenum to tensile tangential stresses at room temperature.

4. With an increase in the degree of preliminary deformation during cold (hot) rolling (up to 70-90%), the capacity of sheet molybdenum for deep drawing will increase.

5. The multioperation deep drawing of parts from molybdenum and its alloys is possible; the distribution of the degree of deformation over the various operations can be recommended, depending upon the relative thickness of the blank with consideration of chemical composition, structure, mechanical properties, and the rate of deformation.

6. Drawing of molybdenum and its alloys according to a combined scheme (with a negative gap between the punch and the die) is possible.

References

1. Savitskiy, Ye. M., G. S. Burkhanov, and Ch. V. Kopetskiy. Metallurgiya i gornoye delo, 1963, No. 5.

2. Braun, Kh., M. Semchishen, and R. Barr. Posledniye dostizheniya v tekhnologii obrabotki litogo molibdena. Tugoplavkiye metallicheskiye materialy dlya kosmicheskoy tekhniki (Recent Achievements in the Technology and Processing of Cast Molybdenum. Refractory Metallic Materials for Space Technology), Izd-vo "Mir", M., 1966.

3. Rubenkova, L. A. and B. A. Shcheglov. Mekhanicheskiye ispytaniya listovogo metalla (Mechanical Testing of Sheet Metal), M., Izd-vo NTO Mashproma, 1963.

4. Korolev, V. N. and A. I. Galakhov. Obzhim trub iz molibdena (Reducing Tubes Made of Molybdenum), "Kuznechno-shtampovochnoye proizvodstvo", 1967, No. 7.

5. Korolev, V. N. Izgotovleniye tonkostennykh detaley malogo diametra iz plastichnykh i maloplastichnykh metallov (Manufacture of Thin-Walled Parts of Small Diameter from Plastic and Low-Plastic Metals), "Kuznechno-shtampovochnoye proizvodstvo", 1966, No. 5.

6. Korolev, V. N. Davil'naya obrabotka tonkostennykh detaley iz molibdena (Press Treatment of Thin-Walled Parts from Molybdenum), "Kuznechno-shtampovochnoye proizvodstvo", 1967, No. 1.

7. Bekhtol'd, D. G. and Ye. T. Vessel'. Perekhod molibdena iz vyazkogo sostoyaniya v khrupkoye (Transition of Molybdenum from the Ductile State to the Brittle State), Sb. "Molibden". M., Izd-vo inostr. lit., 1962.

8. Shofman, L. A. Teoriya i raschety protsessov kholodnoy shtampovki (Theory and Calculations of Processes of Cold Stamping), Mashgiz, 1964.

9. Valiyev, S. A., V. V. Shevelev, and S. P. Yakovlev. Kombinirovannaya vytyazhka tonkolistovogo materiala (Combined Drawing of Thin Sheet Material), "Kuznechno-shtampovochnoye proizvodstvo", 1966, No. 12.

10. Zvorono, B. P. "Vestnik mashinostroyeniya". 1947, No. 6.